

## Tectonic Reactivation in the Indian Ocean : Evidences from Seamount Morphology and Manganese Nodule Characteristics

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**Abstract.** The Central Indian Ocean Basin (CIOB) was subjected to tectonic reactivation in geological past which is unusual for a basin occurring on an apparently single tectonic plate. ENE-WSW trending latitude parallel zone of reactivation across the central part of the basin is reported. Distinct difference in characters of seamounts, manganese nodules and bottom sediment are found in this deformed central part as compared to those from northern and southern parts of this basin. Much lower ratio of height to basal width ( $h/W_b$ ) of seamounts; and presence of several guyots in this central part are reported. Abundance of smaller, spheroidal, smooth textured nodules; and absence of index radiolarian zone I fossil, coupled with sediment erosion of top several centimeters indicate activity of west-bound Antarctic Bottom Water (ABW) and other turbulent water masses that later passed through the reactivated central part. The cause of this deformation is attributed to wrench-faulting as part of large scale tectonic reactivation during late Miocene.

**Keywords :** Indian Ocean, Tectonic reactivation, Manganese nodules.

### INTRODUCTION

The Central Indian Ocean Basin (CIOB) has experienced number of structural movements in geological past. A large scale tectonic deformation (thrusting, subduction and subsidence of the crust) south of Sri Lanka at the margins of Indian and Australian plates has been reported (Eittrheim and Ewing, 1972; Sykes, 1970; Neprochnov *et al.* 1988), which is considered to have started around 7MaB.P. (Cochran *et al.* 1989). In addition, recent study (Mukhopadhyay and Khadge, 1990) on tectono-topography of the CIOB indicates presence of a number of major and minor seamounts. Magma eruption within the oceanic crust is manifested by these seamounts and swells. All these have made the basin (Fig. 1) unstable despite

the fact that the CIOB is located seemingly within, hitherto considered, as belonging to a single Indo-Australian plate.

The most important mineral resource in the CIOB is in the form of manganese nodules. The local facies variation in manganese nodule characters is believed to have been influenced by seamount topography (Mukhopadhyay and Nagender-nath, 1988; Pattan and Kodagali, 1988; Mukhopadhyay and Banerjee, 1989). Distribution and morphology of Manganese nodules show great difference in space in the basin (Mukhopadhyay and Banerjee, 1983; Jauhari, 1990; Banerjee and Mukhopadhyay, 1991).

With this background, the paper presents tectonic reactivation of the CIOB and its contribution to the distribution,

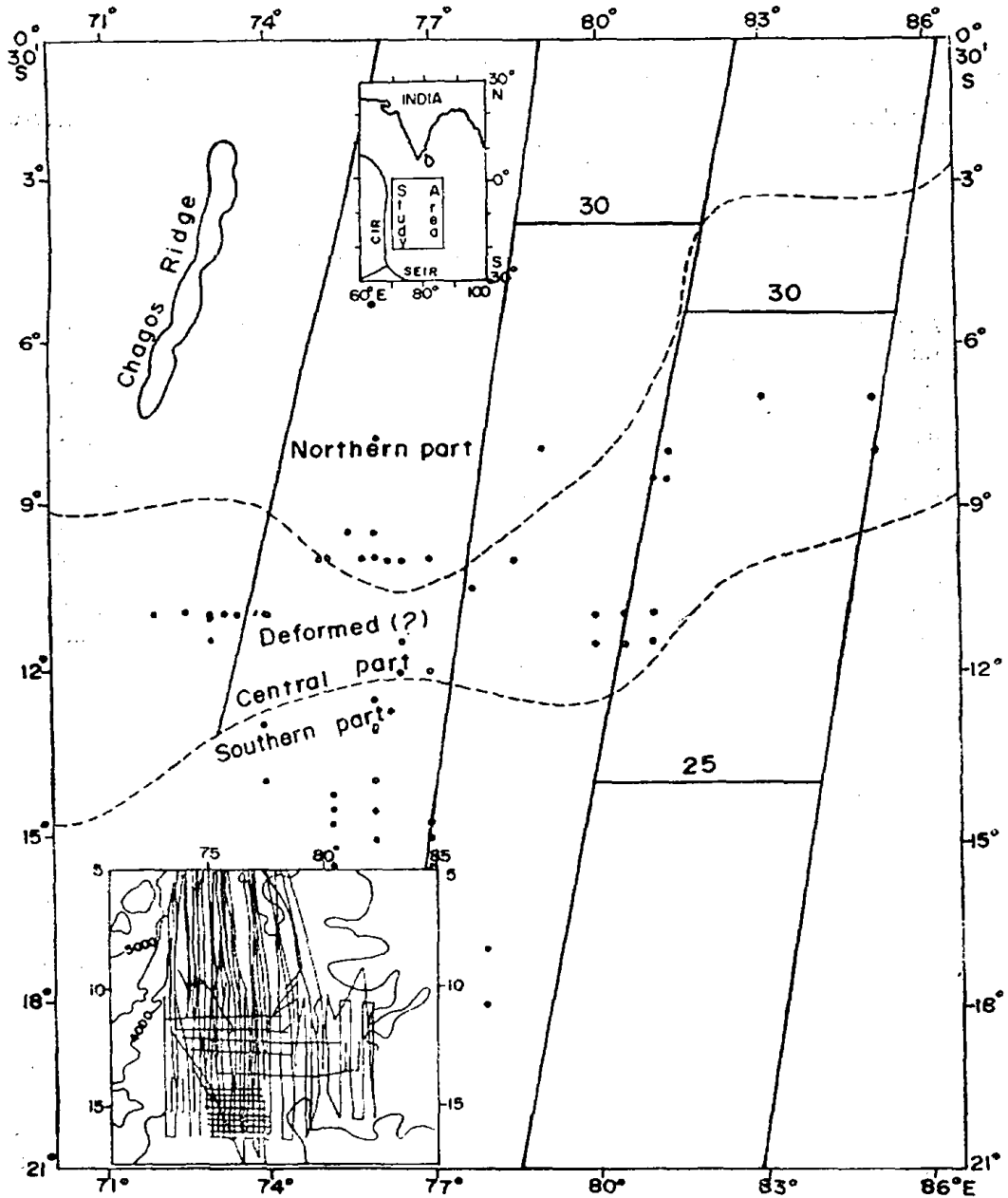


Figure 1. Map showing the study area, divided into three parts. Area bounded by dashed lines is the tentative extension of tectonically deformed and depressed central part. Near N-S trending solid lines are the fracture zones (73E FZ, Indrani FZ, Indira FZ, 86E FZ) with magnetic anomaly numbers. Note the widening of the depressed zone on intersection with fracture zones. Solid dots indicate Mn nodule sampling locations. Inset at the SW corner, shows partial ship tracks of survey. Inset has, however, camouflaged 9 nodule sampling locations.

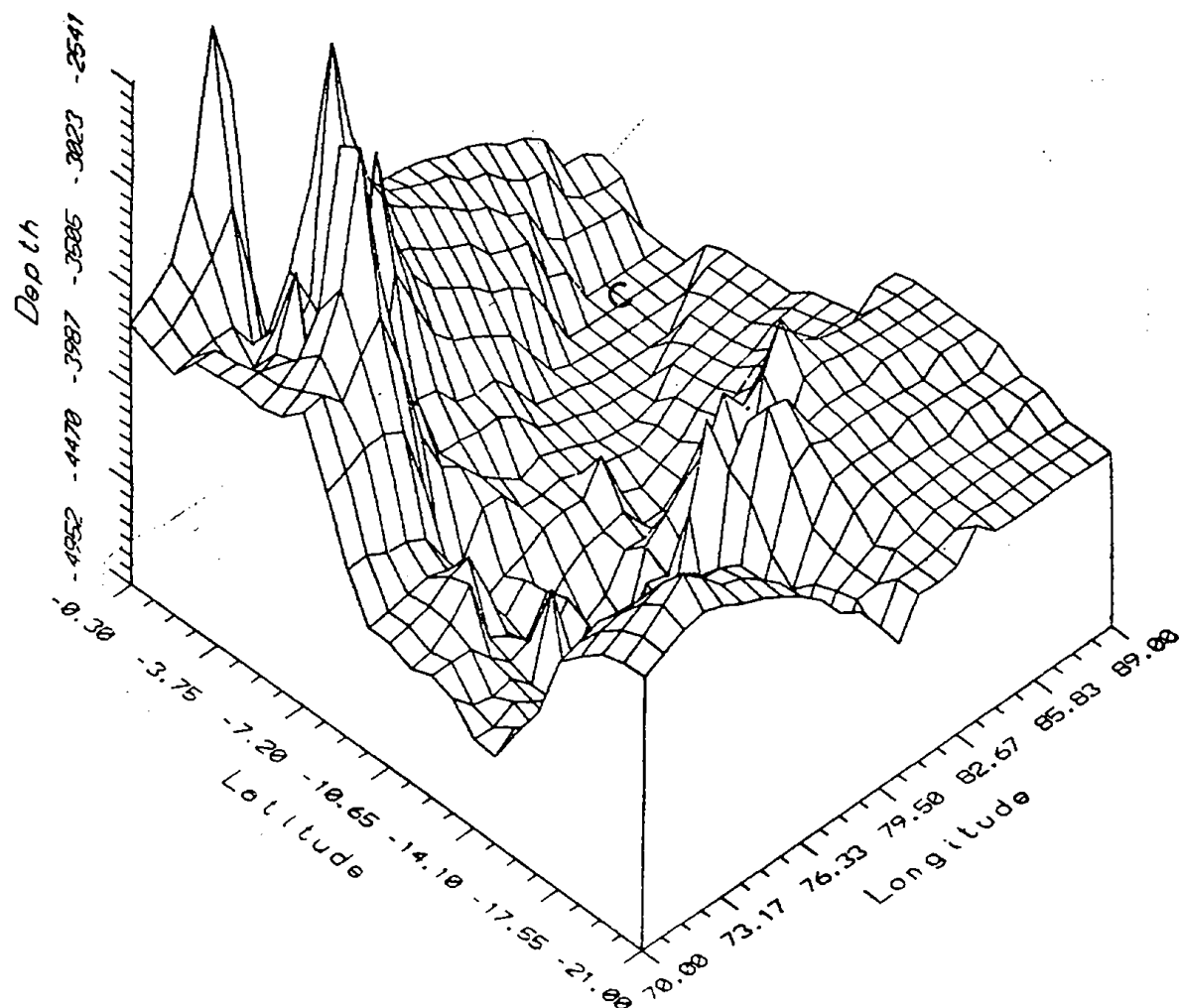


Figure 2. Bathymetry of the seafloor in the study area is shown in three dimension. A prominent long depression (channel ?) travels through the area NE-SSW. This channel marked as 'C', separates the seamounts of higher elevations located north and south of it.

morphology and chemistry of manganese nodules on a regional scale. This is likely to throw light on the relationship between tectonics of the Indian Ocean and mineral resources therein.

#### DATA

Data used for the present study were of two types: 1) Bathymetric data collected by narrow beam echosounder. Water depths at 269 locations were processed to prepare regional bathymetric map (Fig. 2).

A number of seamounts of different heights occur in CIOB. Summit height ( $h$ ), basal width ( $W_b$ ) and summit width ( $W_s$ ) of these seamounts were measured and used to get 3-dimensional fabric (Fig. 3 and 2) Data on distribution, coverage, morphology and chemical composition of Mn-nodules from 70 locations from water depth range of 3256 and 5534m. In addition, some published results (Mukhopadhyay and Banerjee, 1983; Mukhopadhyay and Banerjee, 1989; Banerjee and Mukhopadhyay 1991) are also included.

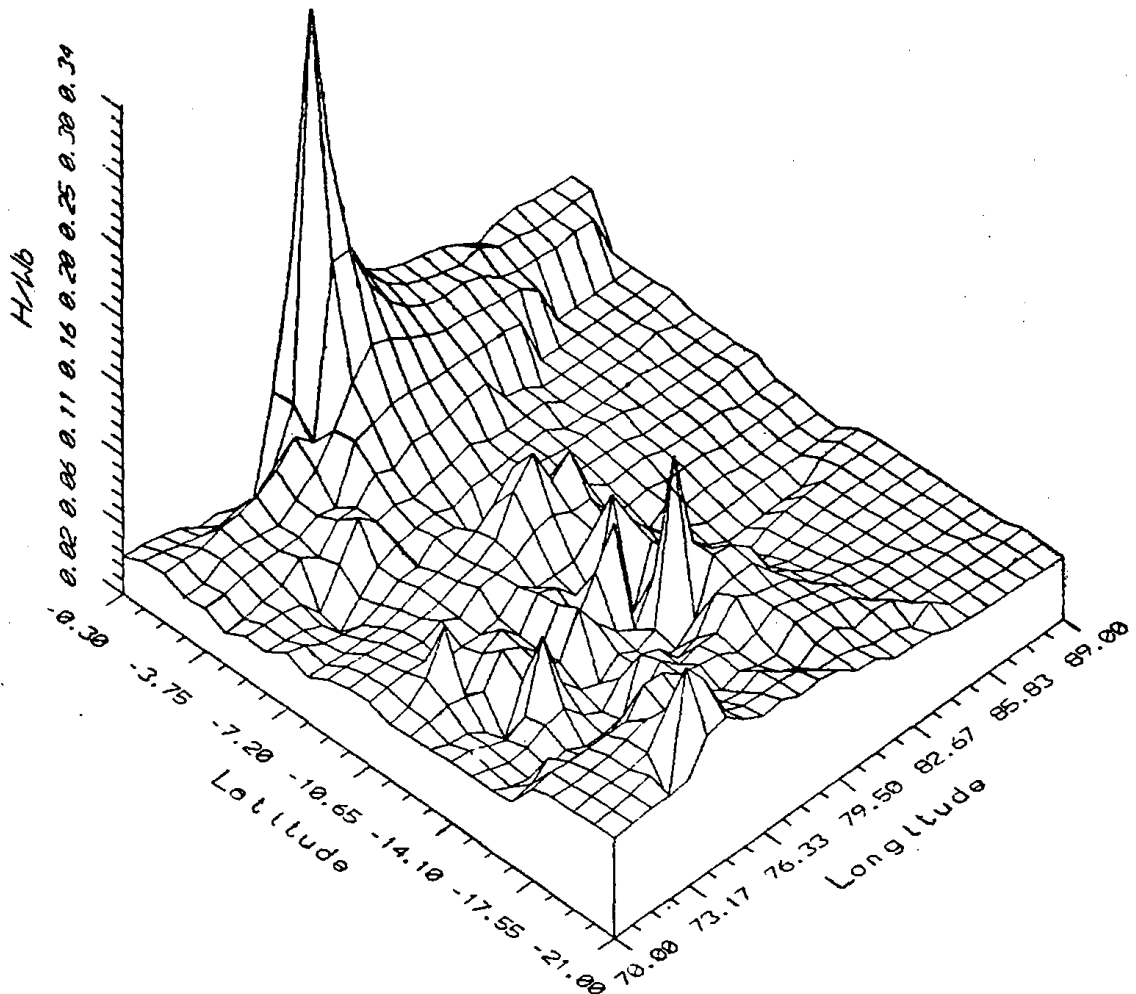


Figure 3. Three dimensional figures show distribution of seamounts having variable ratio of summit height ( $h$ ) to basal width ( $wb$ ). Seamounts occurring on the channel floor show least  $h/wb$  ratio.

#### MORPHOLOGY OF SEAFLOOR

A detailed bathymetry of the study area indicates a large and wide depression trending ENE-WSW, occurring roughly in the central part (marked C, Fig. 2) of the study area. The extension of this zone occurring on Paleocene-Eocene oceanic crust is variable. The width of the zone varies from 178 km along longitude  $76^{\circ}30'E$  to 755 km along  $82^{\circ}30'E$ . Seamounts occurring in this zone are of lesser height and broader base in comparison to those from north and south of this zone (Fig. 3). Sediments occurring in this zone

were largely eroded and at places sediment record of more than 300 ka was found missing (Banakar *et al.* 1991). Large-scale faulting, folding and crumpling are also noticed in this zone. Small ridges and valleys are more in this part of the study area than north and south of it (Fig. 1).

Oceanic crust, in general, subsides with time (Parsons and Sclater, 1977). Similarly, in the present case (Fig. 1), we find Cretaceous oceanic crust at the north records a maximum subsidence (average 1120 m, range 91 to 1133 m). About 90%

of the northern area wherefrom data was available, crustal subsidence of more than 900 m has occurred. Paleocene-Eocene oceanic crust in the central part of the study area shows average subsidence of 601 m (range 61–1147 m). About 62% of the oceanic crust has subsided by more than the average value. However, in two locations, instead of subsidence, oceanic crust in fact has domed up. Miocene-Oligocene oceanic crust in the southern part has subsided on an average by 608 m (range 101–1211 m). About 55% of the sampled area has subsided by more than 600 m since its generation. At least in two locations the crust has domed up, in contrast to normal trend of subsidence. Our findings (manuscript in preparation) thus suggest that crustal cooling and subsequent subsidence increases linearly with the square root of age of the crust and its distance from generation point.

#### SEAMOUNT MORPHOLOGY

The seafloor of the CIOB is perforated by a number of volcanic seamounts. A total of 198 of such seamounts of various heights are traced in the study area. Major seamounts ( $h > 1000$  m) are distributed in two groups—1) seamounts occurring on Cretaceous oceanic crust at the northern part and 2) seamounts occurring on Eocene-Oligocene-Miocene oceanic crust in the southern part. These two groups differ markedly in morphology. The northern seamounts are taller (average  $h = 1950$  m) and wider (average  $W_b = 56.77$  km) than their southern counterparts (1160 m, 17.89 km respectively). Summit height is strongly correlated with basal width ( $r = 0.715$ ) and is 8% of its basal width (Mukhopadhyay and Khadge, 1990).

Seamounts are circular or semicircular in shape and mostly have pointed peaks. Summits of at least 5 seamounts resemble

craters with the central part subsiding to a depth of about 200–250 m. The bathymetric profiles across the summits of two isolated seamounts are shown in Figure 4. Summit depressions are more common in the seamounts occurring on northern older crust supporting the direct relation between lithospheric cooling and subsidence (Parsons and Sclater, 1977; Crough, 1983).

Variation in morphological characters of seamounts from the deformed central part, northern and southern parts of the study area have been noted (Fig. 1). Seamounts in the central part are spaced erratically; their heights do not vary proportionally to their basal width, and show lower  $h/W_b$  ratio than those from the northern and southern parts.

#### MANGANESE NODULE CHARACTERISTICS

Out of the 70 locations wherefrom nodules were sampled, 29 fall in the central part, 10 in the north and the rest 31 occur south of this part. Nodules are not uniformly distributed throughout the study area; and have variable coverage between 20 to 100% of the ocean floor. Nodule abundance, on the contrary, varies from traces to maximum of 18.69 kg/m<sup>2</sup>. The highest average abundance of nodule is recorded at the central part followed by the regions north and south of it (Table I).

Manganese nodules were characterised according to their size, shape, sphericity and surface texture (Table I). Nodules were classified into two groups—(1) small (< 4 cm diameter) and (2) large (> 4 cm diameter). Increasing abundance of small nodules towards south of the study area was noticed. Nodules occurring on the deformed central part are more regular in shape and more spherical than those from other areas. On an average, nodules occurring in the central part show highest

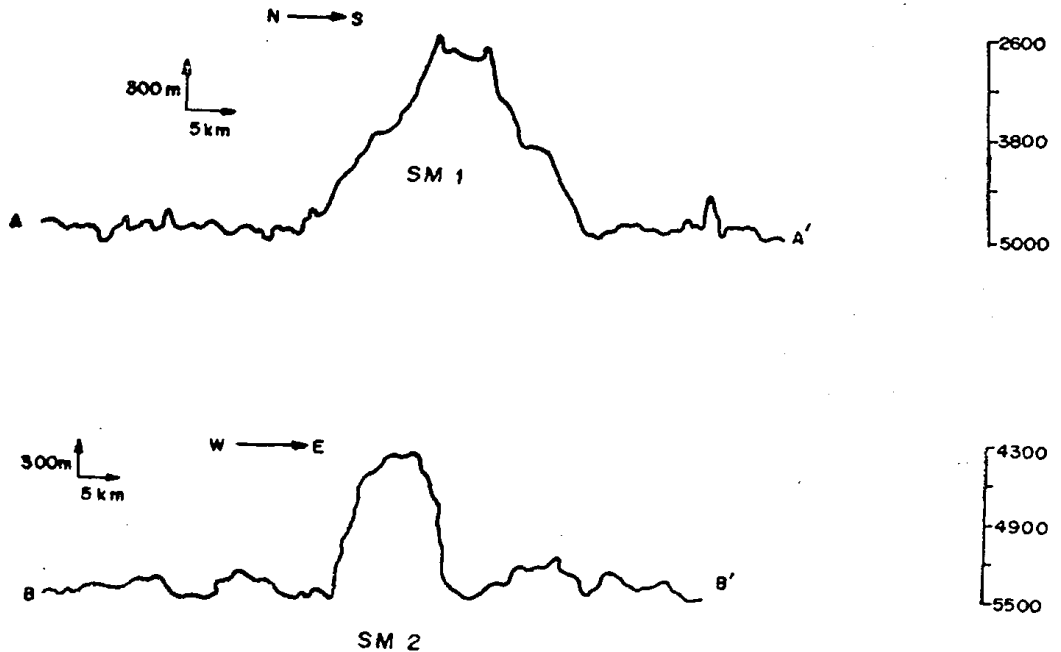


Figure 4. Bathymetric profiles across the summit of two seamounts occurring in the northern (1) and southern (2) parts of the study area. Note the subsided central part of the summit. Seamounts occurring at the central part, however, do not show subsided summit. In contrast they probably had their base subsided due to tectonic reactivation, as indicated by least  $h/W_b$  ratio shown in figure 3.

sphericity (55%); those from northern region have least sphericity (42%) while nodules from the southern part show intermediate sphericity (51%). In all the three regions, smaller nodules are more spherical and regular in shape (subspheroidal, ellipsoidal and oblate) than large nodules.

In some locations nodules are either smooth or rough textured but majority of them show mixed assemblage. Smooth surface nodules are least abundant in the central part, most abundant in the southern part and moderately abundant in the northern part. Surface texture of nodules shows interesting relation with nodule abundance. In the northern part, locations consisting wholly of rough surface nodules, show higher abundance than those having nodules with smooth surface.

In the central part, however, locations with smooth surface nodules show higher abundance ( $9.37 \text{ kg/m}^2$ ) as compared to location with low abundance ( $6.34 \text{ kg/m}^2$ ) of rough nodules. In the southern part, locations with rough surface nodules show marginally low abundance ( $5.64 \text{ kg/m}^2$ ) than locations comprising smooth surface nodules  $6.34 \text{ (kg/m}^2)$ .

Chemical analyses for five elements (Mn, Fe, Ni, Cu and Co) of the nodule samples are presented in Table II. Nodules from the central part show high Mn/Fe ratio and high (Ni + Cu) % and moderate Co%.

#### DISCUSSION

Tectonic framework of CIOB suggests control by tectonic elements of two genetic types (Neprochnov *et al.* 1988). The

TABLE I. Morphology and Distribution of studied Nodules.

Area	No. of stns.	Water depth (m)	* Surface Texture, stationwise					Population (%)			Sphericity (%)		Abundance (kg/m <sup>2</sup> )	Coverage on seafloor (%)
			Smooth	Smooth + Rough	+ Rough Smooth	Rough	Small nodules (< 4 cm)	Large nodules (> 4 cm)	Small nodules (> 4 cm)	Large nodules (< 4 cm)				
Northern part	10	5147 (4492-5335)	3 (30.0)	—	3 (30.0)	4 (40.0)	44.3	55.7	46.6	38.8	6.23 (2.30-12.7)	—		
Central part	29	5005 (3580-5400)	10 (34.5)	2 (6.9)	—	17 (58.6)	59.2	40.8	57.0	52.2	6.43 (0.75-18.7)	69.2 (25-100)		
Southern part	31	4839 (3256-5534)	15 (48.4)	6 (19.3)	5 (16.1)	5 (16.1)	75.2	24.8	55.0	46.8	5.36 (0.77-16.4)	75.4 (20-100)		

\* Figure in parentheses indicate percent/range as the case may be.

TABLE II. Chemical composition of nodules.

Stations Covered	No. of stns.	Mn %	Fe %	Ni %	Cu %	Co %	Mn/Fe	Ni+Cu %
Northern part	10	15.44 (8.4-18.38)	5.63 (3.9-9.4)	0.82 (0.4-1.08)	0.72 (0.28-1.02)	0.06 (0.05-0.12)	3.02 (1.43-4.66)	1.39 (0.78-2.54)
Central part	29	20.56 (10.47-29.11)	7.60 (3.58-14.41)	1.08 (0.25-1.50)	0.93 (0.18-1.5)	0.12 (0.05-0.25)	3.03 (1.22-5.53)	1.99 (0.46-3.00)
Southern part	31	20.81 (12.98-29.63)	9.47 (4.85-14.13)	0.80 (0.39-1.39)	0.73 (0.15-1.42)	0.17 (0.08-0.35)	2.70 (1.07-6.03)	1.46 (0.54-2.29)

first one, parallel to longitudes, occurred during late Cretaceous in the form of large transform faults. The second tectonic element is of smaller magnitude forming cracks parallel to latitudes during post-Cretaceous times. Results of second type reactivation is manifested by intra-plate deformation at the equatorial region below Sri Lanka (Neprochnov *et al.* 1988). This zone, traced between longitude 76°E to 89°E, is 1600 km long and 900–1000 km wide and trends roughly E-W. This zone is represented by largest free-air negative gravity anomaly, and high heat flow (Weissel *et al.* 1980).

Present study shows results of further tectonic activity of second generation in the CIOB along the central part of the study area. This zone extends between latitude 9°S to 15°S area (Fig. 1). The width of this zone is variable particularly in places where it intersects fracture zones. Characteristics of seamounts and manganese nodules from this part indicate probable influence of tectonic elements. The presence of relatively smaller seamounts, lower value of  $h/W_b$  and formations of guyots indicate subsidence of seamounts (Figs. 2, 3). It is also seen (Tables I and II) that the morphology and chemistry of manganese nodules occurring in this central part of the study area differs from others occurring elsewhere.

Both sets of deformations mentioned above, are probably the result of differential stress acting on the Indian plate. Spreading rate about Central Indian Ridge (CIR) increased from 3–4cm/yr in the north to 6–7cm/yr in the south. Subduction rate of Indo-Australian plate below the Eurasian plate at the north is 4–5cm/yr while its northeast subduction rate beneath Sumatra trench was 6.5–7.5cm/yr (Minster and Jordon, 1978). Mid Eocene crust (magnetic anomalies A18) generated by CIR and SEIR (South East Indian Ridge) meet roughly at 15°S

and 73.5°E (Royer *et al.* 1989). Direction of successive anomalies surprisingly becomes north afterwards. Difference in the rate and direction of plate consumption at its northern boundary through collision and at NE boundary through subduction are responsible for such change in orientation of magnetic anomalies, weakening the horizontal balance of compressional stress within the Indian plate. Tectonophysical study on a visco-elastic model suggests that development of inhomogenous shear strain accompanied by dilation and metamorphism causes wrench faulting (Neprochnov *et al.* 1988). Similar situations in the geological past seem to present N-S compressional stress due to collision of India with Eurasia. Extensive N-S compressional stress followed by relaxation in strain in a NE-SW direction (because of high rate of subduction at Sumatra trench) could cause wrench faulting (Neprochnov *et al.* 1988). Our data on seafloor bathymetry, seamount morphology and manganese nodule characteristics substantiate the probability of similar deformation at the central part of the basin.

Manganese nodules found in the central part are more spheroidal, smaller in size, smooth textured and rich in Mn, Ni, Cu in comparison with those occurring in the southern and northern parts of the study area (Tables I and II). The central part further shows high abundance of nodules on channel floor. All these observations indicate influence of seamount topography and effect of nutrient-rich, west-bound AABW and other bottom water masses that passed through this channel. The facts of erosion and lateral transport of top 37 cm of sediment from several cores and absence of distinct Neogene radiolarian zone I biostratigraphic index fossil (*Collosphaca invaginata*) from the sediment column in the central part of the study area, suggest dynamic



strength of bottom water mass (Banakar *et al.* 1991). Highly populated organisms in this water-mass scavenge selective metallic elements from the water column; and on their death and subsequent decomposition release these elements to the sediments. These elements are ultimately absorbed in the manganese nodules from sediments through suboxic diagenesis. In effect, nodules occurring on the channel floor become rich in Mn, Ni and Cu.

Thus, it may be concluded that the central part of the study area had experienced tectonic reactivation in recent geological past. As a result, the seafloor was anomalously deformed with summits of seamounts occurring thereon subsiding; this deformed wrench faulted zone gave way to the westward movement of AABW and other bottom water masses; and this resulted in erosion of sediments corres-

ponding to top 175ka. While distribution of nodules occurring in this central part was controlled by tectonism, subsidence and resultant availability of nuclei, the enrichment of these nodules in Mn, Cu and Ni was brought about by nutrient-rich bottom-water mass. Further detailed exploration of this interesting phenomenon in the CIOB is required to understand the nature of tectonic reactivation and deep-sea nodule occurrence.

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#### References

- BANAKAR, V. K., GUPTA, S. M. and PADMAVATI, V. K. (1991) Abyssal sediment erosion in the Central Indian Basin: Evidence from radiochemical and radiolarian studies. *Mar. Geol.*, v. 96, pp. 167-173.
- BANERJEE, R. and MUKHOPADHYAY, R. (1991) Nature and distribution of manganese nodules from the equatorial Indian Ocean. *Geol. Mar. Let.*, v. 11, pp. 39-43.
- CROUGH, S. T. (1983) Hotspot swells. *Annul. Rev. Earth Science.*, v. 11, pp. 165-193.
- COCHRAN, J. R. and SHIPBOARD SCIENTIFIC PARTY (1989) Initial reports of ODP leg 116. *Proc. Offshore Drilling Program.*
- EITREIM, S. L. and EWING, J. (1972) Mid-plate tectonic in the Indian Ocean. *Jour. Geophy. Res.*, v. 77, pp. 6413-6421.
- JAUHARI, P. (1990) Relationship between morphology and composition of manganese nodules from Central Indian Ocean. *Mar. Geol.*, v. 92, pp. 115-125.
- MINSTER, J. B. and JORDON, T. H. (1978) Present day plate motions. *Jour. Geophy. Res.*, v. 83, pp. 5331-5354.
- MUKHOPADHYAY, R. and BANERJEE, R. (1983) Morphology of polymetallic nodules from the Central Indian Ocean Basin. *NIO Tech.*, Rep. 1/83, 22 p.
- MUKHOPADHYAY, R. and NAGENDERNATH, B. (1988) Influence of seamount topography on the local facies variation in ferromanganese deposits in the Indian Ocean. *Deep Sea Res.*, v. 35, pp. 1431-1436.
- MUKHOPADHYAY, R. and BANERJEE, R. (1989) Underwater geomorphology as a function of the variation in ferromanganese nodule characters in the Indian Ocean. *Curr. Sci.*, v. 58, pp. 115-119.
- MUKHOPADHYAY, R. and KHADGE, N. H. (1990) Seamounts in the Indian Ocean: Indicators of the Indian Plate movement. *Proc. Indian Acad. Sci.*, v. 99, pp. 357-365.
- NEPROCHNOV, Y. P., LEVCHENKO, O. V., MERKLIN, L. R. and SEDOV, V. V. (1988) The structure and tectonics of the intraplate deformation area in the Indian Ocean. *Tectonophysics*, pp. 89-106.
- PARSONS, B. and SCLATER, J. G. (1977) An analysis of the variation of oceanfloor bathymetry and heat flow with age. *Jour. Geophy. Res.*, v. 82, pp. 803-827.

PATTAN, J. N. and KODAGALI, V. N. (1988) Seabed topography and distribution of manganese nodules in the Central Indian Ocean. *Mahasagar*, v. 21, pp. 7-12.

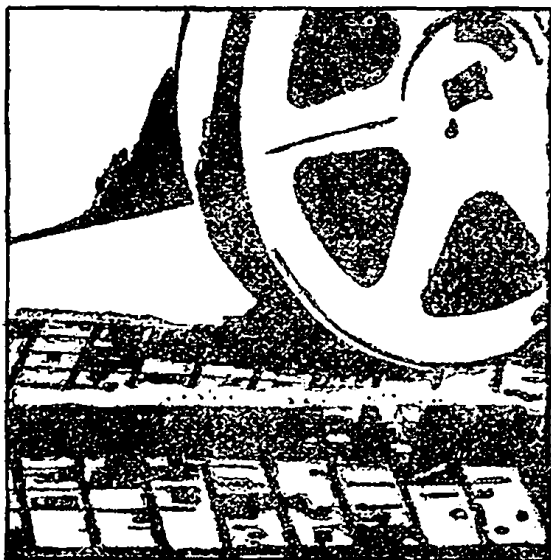
ROYER, J. Y., SCLATER, J. G. and SANDWELL, D. T. (1989) A preliminary tectonic fabric chart of the Indian Ocean. *Proc. Indian Acad. Sci.*, v. 98, pp. 7-24.

SYKES, L. R. (1970) Seismicity of the Indian Ocean and possible nascent island arc between Ceylon and Australia. *Jour. Geoph. Res.*, v. 75, pp. 5041-5055.

WEISSEL, J. K., ANDERSON, R. N. and GEILLER, C. A. (1980) Deformation of Indo-Australian plate. *Nature*, v. 287, pp. 284-291.

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